



Main physical environmental variables driving occupant behaviour with regard to natural ventilation

Fabi, Valentina ; Corgnati, Stefano Paolo; Andersen, Rune Korsholm

Published in:
Proceedings of the 5th International Building Physics Conference

Publication date:
2012

[Link back to DTU Orbit](#)

Citation (APA):
Fabi, V., Corgnati, S. P., & Andersen, R. K. (2012). Main physical environmental variables driving occupant behaviour with regard to natural ventilation. In *Proceedings of the 5th International Building Physics Conference*

General rights

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

Main physical environmental variables driving occupant behaviour with regard to natural ventilation

Valentina Fabi¹, Rune Vinther Andersen², and Stefano Paolo Corgnati¹

¹ *TEBE Research Group, Department of Energy, Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129 Torino, Italy*

² *ICIEE, Department of Civil Engineering, Technical University of Denmark, Nils Koppels Allé Building 402, 2800 Kgs. Lyngby, Denmark*

Keywords: occupant behaviour, ventilation, influencing factors, modelling

ABSTRACT

Energy consumption in buildings is influenced by building properties, building controls and the way that these are used by the occupants of the building.

This paper focuses on natural ventilation concerning the occupants' habits of opening/closing the windows in residential buildings. Preeminent variables influencing the occupants' use of windows are investigated and the main results of a literature review are highlighted. Statistical analysis of data coming from measurements of occupants' window opening, conducted in 15 dwellings in Denmark, are developed to infer the probability of opening and closing windows and to determine relationships between environmental conditions and the occupants' window opening behaviour. The main physical environmental variables that have been found to be important drivers in determining the action to open or close windows are defined on the basis of the measurements.

The ultimate goal is to provide more accurate information about driving forces related to the window opening and closing behaviour.

1. Introduction

The occupants' actions related to the building control systems, such as ventilating an indoor environment, is generally neither a simple reflex action nor a rational well thought out act. Nevertheless, among individuals or even households, behaviour appears to be fairly consistent, indicating that a "subjective rationality" exists in behaviour. This implies that people normally try to act in a way which is defined as "as good as possible" by themselves [Dubrul, 1988].

People act within a framework of factors, including physical environmental parameters (e.g. air temperature, CO₂ concentration), contextual parameters (for example the quality of buildings, such as air tightness, or the availability of facilities to control the indoor climate such as operable windows), social factors (such as economical resources, like income) and physiological factors (age, gender, health). The behaviour of people is also influenced by factors such as attitudes, preferences and expectations (psychological factors). [Fabi et al., 2011].

In a view of these factors, it is not surprising that a large variation in behaviour is found among buildings. As buildings become more energy efficient the behaviour of occupants plays an increasingly important role in consumptions (Jeeninga et al., 2001; de Groot et al., 2008; Haas et al., 1998; Papakostas and Satiropoulos, 1997; Andersen et al., 2009). As a consequence, there are often large discrepancies between the calculated or simulated energy performances and the measured actual energy performances in real buildings. The wide variation in energy consumption in buildings with the same physical characteristics is attributed to differences in occupancy patterns and behaviour of the occupants, when the building is occupied (Jeeninga et al., 2001; Haas et al., 1998; Linden et al., 2006; Branco et al., 2004). In particular, the use of windows affects ventilation rates and consequently

influences the amount of energy consumption. A considerable difference between the standard values of ventilation used for simulations (e.g. for building energy certification) and the ventilation patterns in real occupied buildings may be expected. Due to the close relationship between occupant behaviour and energy consumption, it is important to define these behaviour patterns: according to Andersen et al. [2009] the definition of a set of standard behaviour patterns based on the estimation of real inhabitants' behaviour is required to improve the accuracy of the outcomes of the simulations.

Groups of individual households displaying similar types of behaviour can be discerned from a wide range of cases to characterize the occupant behaviour in terms of patterns or profiles to be used as input data in energy building simulations. This makes possible to generalize patterns of behaviour and to improve the accuracy of the calculation tools for simulation of building performances.

In this paper we first present the results of a literature survey of window opening behaviour research. We then go on to present the results of a field monitoring campaign in Danish dwellings. From the data collected in the measurements, the probability of opening and closing a window (change from one state to another) has been inferred as a function of several indoor and outdoor variables separately, since the driving forces for opening and closing a window might be different (e.g. the window might be opened due to IAQ and closed because of low indoor temperature). The final goal of the paper is to derive the most dominating driving forces useful for a more accurate description of occupant behaviour related to the habits of opening and closing the windows.

2. Literature survey of Investigation on window opening behaviour in residential buildings

Investigations on windows opening behaviour and natural ventilation have mainly been carried out with two aims: to find if occupants are provided with adequate fresh air and to

highlight the influence on energy consumptions. The former category of studies has usually been carried out in dwellings with a health or a comfort perspective, while the latter category has mostly been studied in office with a comfort and energy performance perspective. So far, there are only few investigations regarding occupant behaviour in residential buildings. As a consequence, the existing models of occupant behaviour implemented into energy simulation software are mainly based on data from office buildings.

2.1 Identification of driving forces

The use of windows affects ventilation rates in dwellings and consequently influences both the amount of energy required in buildings and the indoor climate. Since the air change rate has a big impact on the energy consumption, it is evident that different window opening behaviour patterns will result in different energy consumptions.

Bedford et al. (1943) conducted 358 measurements of the air change rate in six properties in London using the decay of coal-gas (containing about 50% of hydrogen) liberated into the air. They discussed the effects of flues, air gratings, cracks and leakages on the air change rate in the houses and finally noted that any reasonable amount of ventilation could be obtained if liberal window openings were provided. They obtained as many as 30 air changes per hour by means of cross-ventilation in experimental rooms. Since then, houses have been tightened and sealed, increasing the relative effect of window opening on the air change rate. In fact, when Wallace et al. (2002) measured air change rates in a house in Virginia during a year, they found that the window opening behaviour had the largest effect on air change rates, causing increases ranging from a few tenths of an air change per hour to approximately two air changes per hour. In another paper describing the same measurements, Howard-Reed et al. (2002) stated that opening of a single window increased the air change rate by an amount roughly proportional to the width of the opening, reaching increments as high as 1.3 h^{-1} . Multiple window openings increased the air change rate by amounts ranging from 0.10 to 2.8 h^{-1} .

While Bedford et al. (1943) found an average air change rate of 0.8 h^{-1} and with only 11 % of the measurements under 0.4 h^{-1} in London, Offerman et al. (2008) found that 75 % of homes without mechanical ventilation had air change rates lower than 0.35 h^{-1} , suggesting that homes had been tightened to such an extent that occupants needed to actively adjust building controls to obtain adequate supply of fresh air. Also, Price and Sherman (2006) found that, depending on season, between 50 % and 90% of Californian homes had air change rates lower than 0.35 h^{-1} .

According to Keiding et al. (2003) who conducted a questionnaire survey in Danish Dwellings, 53.1 % slept with an open window during autumn while 25.2 % had a window open during the night in winter time, which in most situations should ensure an air change rate of more than 0.35 h^{-1} . They found that 91.5 % of the respondents vented by opening one or more windows each day throughout the year. The results showed that a large proportion of Danish occupants use windows to adjust the supply of fresh air to the dwelling. The effects of this behaviour on the energy consumption might be substantial. However, when Bekö et al. (2010) measured ventilation rates in 500 bedrooms of Danish children, they found that approximately 57 % of the children slept in bedrooms with air change rates lower than

0.5 h^{-1} . In their study the average air change rate in the 500 bedrooms was 0.46 h^{-1} . This was considerably lower than the results of Kvistgaard et al. (1985), who measured air change rate and temperature in 16 Danish dwellings and found an average air change rate of 0.68 h^{-1} .

In a later paper Kvistgaard and Collet (1990) noted that there was considerable difference in the total air change between the individual dwellings. As the basic air change was fairly similar in the dwellings, it was concluded that cause of the large differences on air change was due to the users (i.e. the behaviour of the occupants). This conclusion was confirmed by Wehl (1986), who concluded that a substantial variation in ventilation behaviour found among seven households, reflected different occupant functions and management strategies.

Iwashita, G and Akasaka, H EaB (1997) were able to quantify the effect of occupant behaviour on air change rate. They investigated the relationship between occupants' behaviour and the energy consumption used for air conditioning, by means of tracer gas measurements and questionnaire surveys in Japan, and concluded that 87% of the total air change rate was caused by the behaviour of the occupants.

One aspect that affects the air change rate is how often and how long the windows are opened but also the degree of opening will have an impact.

2.1.1 Windows opening and closing

Since the effectiveness of natural ventilation is strongly dependent on characteristics of ventilation openings and their controllability (aspects closely related to the type and size of the windows and its placements within the facade) the window opening and closing behaviour is strictly connected to the building characteristics. Type of dwelling (single house or apartment), orientation and type of the room (bedroom, living room or kitchen) are the main parameters found to have an influence on occupant behaviour related to window opening and closing.

As early as 1988, the study of IEA-ECBCS Annex 8 (Dubrul, 1988) on occupant behaviour with respect to ventilation involving Belgium, Germany, Switzerland, the Netherlands and the United Kingdom focused on a combination of questionnaires and observations to determine which action is taken by occupants to ventilate their homes and to evaluate their reasons for these actions. The study have shown that the type of dwelling (house or apartment) influences the length of time windows are open and has an effect also on how wide windows are left open. In the same research it appeared that in houses compared to apartments, windows in living rooms and kitchens were open on average for shorter periods, whereas windows in bedrooms were open for longer. The type of the dwelling (detached one-story residence) was found to affect the residential openness in the pilot study conducted by T. Johnson and T. Long (2005) in North Carolina between October 2001 and March 2003.

According to the study of IEA - Annex 8 (Dubrul, 1988) the main ventilation zones are bedrooms, while the greatest percentages of windows which are never opened are in living rooms, kitchens and bathrooms. This finding is consistent with the study of H. Ernhorn (1988) in 24 identical flats in Germany (1984). Even in the extreme winter weather, bedrooms are ventilated more frequently than all of the

rooms on average: during the entire measuring period the windows opening time in bedrooms exceeds the average for all rooms by some 50%. The orientation of rooms is important as well. The IEA-ECBCS Annex 8 project (Dubrul, 1988) found that, when the sun was shining, south facing living rooms and bedrooms were more likely to be ventilated for longer periods than similar rooms orientated in other directions.

The investigations have shown different daily patterns for different types of the rooms. Typically, the maximum of window openings is in the morning. During early afternoon (when cooking) the number of windows open is still relatively high, but gradually decrease during the afternoon till the return home of working inhabitants (at about 5 p.m.). Time of the day is found to determine the transition probabilities (closed to open and open to closed) in the aforementioned study of Johnson and Long (2005).

The window opening behaviour is strongly related to the perception of comfort with respect to the indoor climate in dwellings. Due to this correlation the most important environmental parameters are investigated in many studies of occupants' window opening behaviour.

Not surprisingly, the outdoor temperature had a considerable impact on the window opening behaviour. An earlier study of J.B. Dick and D.A. Thomas (1951) found that the outdoor temperature was the single most important explanatory variable when investigating the number of open windows in 15 houses. Most of the investigation in the IEA-ECBCS Annex 8 project (Dubrul, 1988) have shown that in the temperature range between -10°C to $+25^{\circ}\text{C}$ a direct linear correlation exists between window use and outdoor temperature. Brundrett (1979) found the temperature (mean monthly temperature and average temperature swing) to be an important explanatory variable for the occupant's opening of windows. Erhorn (1988) found that a change in ventilation behaviour is to be stated at temperature of 12°C : generally, below 12°C daytime ventilation increases by some 75% per degree temperature differences, above 12°C by some 1.1% per $^{\circ}\text{C}$. In terms of ventilating frequency this represents an increase of about 50%. The results of Andersen et al (2009) are consistent with these findings. The statistical analysis related to the questionnaire survey carried out in 2006 and 2007 in Danish dwellings has shown that window opening behaviour is strongly linked to the outdoor temperature. Later in this paper, the authors will present results of logistic regression models based on long-term monitoring of behaviour and environmental variables in 15 dwellings. These confirm that outdoor temperature, indoor temperature, solar radiation and the indoor CO_2 concentration were the most influencing variables in determining the opening/closing probability.

The season is found to be correlated with the window opening behaviour in Erhorn (1988): windows are open longest in summer and shortest in winter. In August the overall opening time for all windows amounts to about 25% on average and it decreases to about 5% in winter. This finding is supported by the successive study conducted by Herkel et al. (2008) in office buildings, where the percentages of open windows are highest in summer, lowest in winter and intermediate in autumn and spring. Regarding the seasonal variations, the open question is, if it is the season itself or the changes in outdoor conditions that drive the occupant behaviour.

The IEA-ECBCS Annex 8 (Dubrul, 1988) showed that windows are opened more often and longer periods in sunny weather, the findings of Andersen (2011) fit with these earlier studies. In Erhorn's investigation (1988) a distinct dependence on solar radiation cannot be confirmed, as the influences of outdoor air temperature and global irradiance are superimposed.

The influence of wind speed was investigated in all the aforementioned studies, and the results are coherent in finding a significant decrease in the prevalence of open windows at high wind speed: above wind speed of about 8 m/s nearly all windows were closed.

The interaction between occupant's gender and perceived illumination had a statistical impact on the window opening behaviour (Andersen, 2009).

The investigation of Guerra Santin (2010) of households in the Netherlands in autumn 2008 fits with the Annex 8 results (Dubrul, 1988): a Chi-squared test showed that the occupant presence was associated with fewer hours per day of open windows in living rooms and bedrooms, while the presence of children at home was associated with keeping windows closed in the living room.

IEA-ECBCS Annex 8 project (Dubrul, 1988) highlighted a clear correlation between smoking behaviour and the airing and ventilation of living rooms: where occupants smoke the living room was ventilated on average for twice as long as in non-smoking households. Moreover, the longer the dwelling was occupied the more the windows, especially the bedroom windows were kept open, and in this way the Annex 8 concluded that the presence of the occupants in the home and use of the windows were related.

Finally, IEA-ECBCS Annex 8 (Dubrul, 1988) highlighted that indoor climate preferences in terms of temperature are one key driver of the behaviour of the occupants, but this driver is strongly connected to the occupant's perception of comfort.

2.1.2 Degree of opening

In the various projects conducted for IEA-ECBCS Annex 8 (Dubrul, 1988), three levels of opening (closed, slightly open and wide open) were examined. Large variations in the opening levels were found: the Dutch team observed a tendency towards a larger percentage of wide open windows, while the Belgian team's findings, based on interviews with the occupants in 2400 social houses, showed a trend towards slightly open windows.

The weather also influences the degree of opening of windows. The studies conducted for the Annex 8 project showed that fanlights were left open for more than eight hours in 17% and 8% of living rooms when the outside temperature was 5°C and -8°C respectively. Moreover, an outside temperature change from 15°C to -5°C produced changes in the percentage of open or slightly open windows from 41% to 34% in the mornings and from 32% to 24% in the afternoons. For the main bedrooms these figures are 70% to 64% and 55% to 44% respectively.

2.1.3 Ventilation Type

The study of Erhorn (1988) comparing the duration of window ventilation with naturally ventilated flats according to Brundrett (1979), concluded that in flats without

mechanical ventilation system, windows are open about four times as long as in mechanically ventilated flats. This result is inconsistent with the IEA-ECBCS Annex 8 Report (Dubrul, 1988), where only small differences were found between dwellings without mechanical ventilation and dwelling with various types of ventilation systems. The interviews described in the report showed that the occupants had no understanding of how to use the mechanical ventilation system.

The IEA Contributed Report 08 by J.E.F. Van Dongen (2007) examined the influence of specific ventilation systems on the active ventilation behaviour. It was found that the occupant controlled ventilation was only partly related to the type of

ventilation device installed in the dwellings: in living rooms, the mechanical ventilation system tended to influence the ventilation by behaviour, in the bedroom the behaviour tended to be independent of the installed system.

Moreover, the Annex 8 projects (Dubrul, 1988) found that windows in centrally heated dwellings were less likely to be opened for long periods than those in non-centrally heated dwellings and that dwellings with warm-air central heating were ventilated less than dwellings with radiators systems.

In summary the previously identified driving forces for energy-related behaviour with respect to ventilation / window operation are grouped and listed in Table 1.

Table 1. Driving forces for energy-related behaviour with respect to ventilation / window operation.

biological	psychological	Social	time	physical environment	building/equipment properties
Age	Perceived illumination	Smoking behaviour	Season	Outdoor temperature	Dwelling type
Gender	Preference in terms of temperature	Presence at home	Time of day	Indoor temperature	Room type
				Solar radiation	Room orientation
				Wind speed	Ventilation type
				Co2 concentrations	Heating system

2.2 Models of window opening behaviour

In general, the existing models of window opening behaviour express the probability of actions performed on windows in office buildings: therefore they are not calibrated and validated for residential buildings. So far, there are only two published models regarding the window opening behaviour in dwellings.

In 2005 Johnson and Long developed a linear regression model: a series of stepwise linear regression analysis were performed on the data to identify factors associated with open windows and doors. The statistical analyses were focused on identifying the variables that could be used to predict when a residence will have one or more open windows or doors.

In 2011 Andersen et al. developed a logistic model inferring the probability of opening and closing a window (change from one state to another) separately to determine the most dominating drivers for each action. For each variable the coefficients for the logistical regression was identified for different times of day and day of week. Furthermore, the magnitude of each variable's maximum impact on the probability of opening or closing a window was presented.

Haldi and Schweiker (2011) have recently verified models developed for office building in residential buildings. Their analysis were based on data from two distinct measurements campaigns in residential indoor environments in Japan and Switzerland. The calibration and the verification were conducted for several modelling approaches of varying complexity with respect to the number of variables included in the models. The previous models for office occupants' use of windows are related to the study of Haldi and Robinson (2009) and Schweiker and Shukuya (2009). In particular, they tested the Bernoulli process, Markov Chain and hybrid model, each of them including a set of variables retained on the basis of forward selection. And the Bernoulli process focusing carefully on the optimal choice of variables. Totally,

the combination of these distinct approaches resulted in nine type of models for the prediction of actions on windows. In the case of the Swiss dataset, the analysis demonstrated the ability of carefully formulated behavioural models inferred from data from offices to reliability predict window usage in a residential context and vice-versa. The same models performed less satisfactorily in the Japanese residential database. From these results it seems that such models require specific calibration in the case of buildings equipped with an air-conditioning unit as was the case of Japanese database.

3. A field survey in Denmark

Measurements of window opening and closing behaviour along with indoor and outdoor environmental variables were conducted in 15 dwellings located in the area of Copenhagen, Denmark, during the period from January to August 2008.

Measurements were carried out in 10 rented apartments and 5 privately owned single family houses. Half of the apartments were naturally ventilated while the other half were equipped with constantly running exhaust ventilation in the kitchen and bathroom. Three single family houses were naturally ventilated, while the other two were equipped with exhaust ventilation. The measurements were carried out in one living room and one bedroom in each dwelling.

The following variables were measured at 10 minute intervals in all 15 dwellings.

- Indoor environment parameters:
 - Temperature [°C]
 - Relative humidity [%]
 - CO₂ concentration [ppm] (used as a proxy for IAQ)
- Outdoor environment parameters
 - Air temperature [°C]
 - Relative humidity [%]
 - Wind speed [m/s]
 - Solar radiation [W/m²]

- Window state (open/closed)

In the main analyses, the probability of opening or closing a window (change from one state to the other) was inferred rather than the probability of an open window (state).

3.1 Statistical analysis

The objective of the measurements was to define standardised occupant behaviour patterns, suited for simulation purposes. The authors did actually try to model each dwelling by itself, but that resulted in 15 different models, which were not feasible to include in a simulation programme. Since the 15 models were different and did not show similarities, the authors decided to group the buildings according to their ventilation principle and ownership, since this has previously been shown to influence the occupants' window opening behaviour (Andersen et al. 2009). The 15 dwellings were divided into 4 groups depending on the ownership (owner-occupied or rented) and the type of ventilation (natural or mechanical). The initial models revealed many significant interaction terms. This showed that occupants' window opening behaviour was governed by complicated relations between several variables: a model with many interaction terms between continuous variables may be too impractical for the current standard of simulation programs. Because of this, the authors developed a simpler model for each group of dwellings with a limited number of interaction terms between continuous and nominal variables.

The analyses were conducted using the statistical program R to perform multivariate logistic regression using AIC for the variable selection in the regression model. AIC is a biased estimator giving the measure of the relative goodness of fit of a statistical model. For each variable the coefficients for the logistic regression was inferred for different times of day and type of room. The measure of the maximum impact of the variable on the probability of opening or closing a window is given through the magnitude of the variable.

The models predict the probability of an action (opening or closing) using equation 1, where p is the probability of opening/closing a window, a and b_n are the coefficients in the tables and x_n are the associated variables (temperature, CO₂ concentration etc.). Moreover, this equation takes into account the interactions between variables by adding interaction terms to the model.

$$\log\left(\frac{p}{1-p}\right) = a + b_1 \cdot x_1 + b_2 \cdot x_2 + \dots + b_n \cdot x_n + c_{12} \cdot x_1 \cdot x_2 + c_{13} \cdot x_1 \cdot x_3 + \dots \quad (1)$$

3.2 Results

The results coming from the analysis conducted into 15 Danish dwellings confirmed that there is not an always valid model to characterize the user and its behaviour, but only a suitable model according to the goal of the analysis.

The outdoor temperature, indoor temperature and the indoor CO₂ concentration (used as a surrogate IAQ indicator) were the most important variables in determining the window opening/closing probability.

The four groups are divided on the basis of ownership and type of ventilation, and from the four models it appears that some common patterns of behaviour exist. In naturally ventilated dwellings, CO₂ concentration has an impact in the models of opening windows, while outdoor temperature has an impact for closing windows. In mechanically ventilated dwellings lux values are included in both the groups, whereas outdoor temperature and solar hours are being found to have an impact on the probability of closing windows.

Looking at the four groups, the three most important variables in determining the probability of opening a window were the CO₂ concentration, outdoor temperature and the lux values. For the outdoor temperature and lux values, this was also the case for closing of a window, although the direction was different.

Interestingly, wind speed is not found a variable influencing behaviour in any model of the four groups.

4. Discussion

According to the literature survey, the influence of physical environmental drivers and contextual drivers (time, season, building equipment and properties) has been highlighted.

The main variables investigated resulting to be driving forces for the four different groups of dwellings are presented in table 2 and in table 3 with their magnitudes.

Table 2. Driving forces for energy-related behaviour with respect to opening/closing windows for the investigated dwellings.

	Open windows				Close windows			
Investigated variables	Group 1	Group 2	Group 3	Group 4	Group 1	Group 2	Group 3	Group 4
Time of day	x			x	x		x	x
Room type	x		x	x	x	x	x	x
Season	x			x	x			x
Indoor temperature	x			x			x	
Outdoor Temperature					x	x	x	x
Indoor Relative humidity	x				x		x	x
Outdoor relative humidity		x			x			x
CO ₂ Concentration	x	x	x					
Solar radiation	x			x		x		
Solar hours						x	x	x
Lux		x				x		x

Table 3. Magnitudes of resulting driving forces for energy-related behaviour with respect to opening/closing windows for the investigated dwellings.

Investigated variables	Open windows				Close windows			
	Group 1	Group 2	Group 3	Group 4	Group 1	Group 2	Group 3	Group 4
Indoor temperature	2.15			6.18			2.39	
Outdoor Temperature					0.15	7.85	4.28	14.15
Indoor Relative humidity					0.04		1.84	2.88
Outdoor relative humidity		1.48			0.02			37.30
CO ₂ Concentration	4.04	3.47	4.16					
Solar radiation	3.42			6.93		4.04		
Solar hours						0.86	1.27	0.86
Lux		1.44		1.23		3.93		0.79

Based on the studies conducted so far, we chose to measure in the main bedroom and the main living room in each dwelling, since in findings the percentage of open windows in kitchens and bathrooms was similar to that of living rooms. In our survey, the main ventilation zones are bedrooms where the probability of opening and closing windows is higher than the living rooms for the analyzed dwellings.

Referring to single houses or apartments, the dwelling type is analyzed as well. In particular, all the owner-occupied dwellings are single houses and all the rental ones are apartments. The study highlighted that in single family houses the average frequency of openings is less than in apartments: in single family houses the frequency average of openings is 173.8, whereas in the apartment is 224.2.

This field survey highlighted that for all the examined groups the inhabitants have generalized patterns regarding the time of the day: the probability of opening windows is highest in the morning (6-9 a.m.) when they wake up (figure 1).

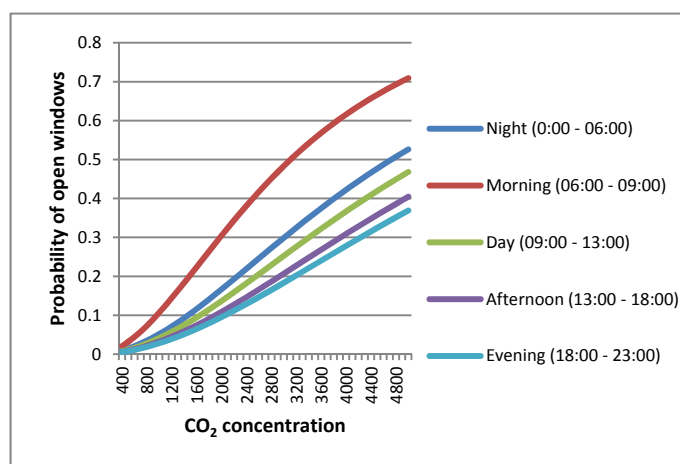


Fig. 1. Probability of opening windows for different times of day and CO₂ concentration for group 1 of dwellings.

The study confirmed the strong relationship linking the windows opening and closing behaviour with perception of comfort with respect to the indoor environmental quality.

As described in the results section, temperature, both outdoor and indoor, was the most important variable in determining the probability of opening and closing a window. Whereas it appears outdoor temperature together with indoor temperature (group 3 for closing windows, table 2), the magnitude of the impact on the probability was roughly twice as high as for the indoor temperature, otherwise it appears only outdoor temperature as driver for closing windows. Only indoor temperature is a reason for opening windows.

Regarding the seasonal variations, our study supported the previous research of Erhorn and Herkel et al. Season is found to be correlated with the opening behaviour: for all the four analyzed groups the highest percentage of openings is in spring and the lowest is in winter. Moreover, the investigations show interactions between season and some of the variables. As a consequence, outdoor temperature, indoor temperature and solar radiation are found to have different impact on probability of opening and closing windows in the different periods of the year.

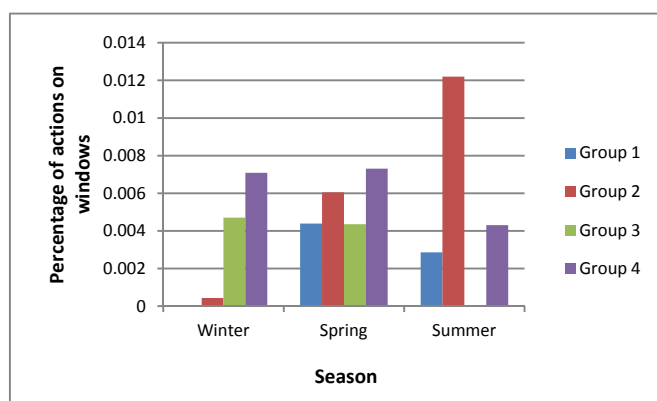


Fig. 2. Percentages of actions performed by users on windows in different periods of the year.

Solar radiation has a high impact on windows opening behaviour and the daily hours of sun were found to be drivers for windows closing behaviour, confirming the relationship between windows opening and sunny weather.

Since ventilation type has been a criterion for the categorization of dwellings in groups, it has been studied which variables influenced in different way the naturally and

the mechanically ventilated dwellings. Surprisingly, the frequency of openings is higher in mechanically ventilated houses (frequency average 277 openings) than in naturally ventilated houses (frequency average 147 openings).

Regarding the variables influencing the windows opening and closing behaviour patterns, in naturally ventilated dwellings, CO₂ concentration has an impact in the models of opening windows, while outdoor temperature has an impact for closing windows. In mechanically ventilated dwellings lux values are included in both the groups, whereas outdoor temperature and solar hours are being found to have an impact on the probability of closing windows.

Physiological drivers like age or gender and psychological drivers like the preferences about indoor climate in terms of temperature are not included into investigations.

5. Conclusion

The analyses of window opening behaviour in residential buildings are still relatively few, and the problem of modelling the occupant behaviour only partly solved.

The performed literature review highlights that what seems to be a simple task, as to open or close windows is in reality a task that is influenced by many factors, which interact in complex ways. It is evident that these simple and multiple interactions with building controls have a very big impact both on the indoor environment quality and on the energy consumed to sustain the desired indoor environmental quality level. The fact that there are many drivers of occupant behaviour seems to be largely ignored in the field of modelling: an increase of accuracy in modelling window opening behaviour is a clear example. Here the tendency is to focus on thermal comfort and view the effects from other drivers as random variations.

The results and analyses of the survey conducted in Denmark presented in this paper fitted with the results of the previous studies and indicated that the window opening behaviour was governed by different but distinct habits in the different dwellings. Within the physical environmental parameters, the outdoor temperature, the indoor temperature and the indoor CO₂ concentration proved to be the three most important variables in determining the probability of opening and closing a window. Dwelling type, room type and time (both of the day and of the year) confirmed to be variables influencing the inhabitants' behaviour.

Based on the measurements a definition of occupant behaviour patterns in building simulation programs is proposed as well. When implemented into simulation programs, this definition will significantly increase the validity of the simulation outcome.

References

- Andersen R.V., Toftum J., Andersen K.K., and Olesen B.W. 2009. Survey of occupant behavior and control of indoor environment in Danish dwellings, *Energy and Buildings* 41, 11-16.
- Andersen R.V., Olesen B.W., and Toftum J., 2011. Modelling window opening behaviour in Danish dwellings. *Proceedings of Indoor Air 2011: the 12th International Conference on Indoor Air Quality and Climate*, Austin, Texas.
- Bedford, T., Warner C.G., and Chrenko F.A.. 1943. Observations on the natural ventilation of dwellings. *Journal of the royal institute of British architects*.
- Bekö G., Lund T., Nors F., Toftum J., and Clausen G. 2010. Ventilation rates in the bedrooms of 500 Danish children, *Building and Environment* 45, pp.2289-2295
- Brundrett. G.W., 1979. Window ventilation and human behaviour, in P.O. Fanger and O. Valbjorn (eds.), *Proceedings 1st International Indoor Climate Symposium*, Copenhagen, pp. 317-325.
- Dick J.B., D. Thomas A., 1951. Ventilation research in occupied houses, *Journal of the Institution of Heating and Ventilating Engineers*, 19(194), 279-305.
- Dubrul C., 1988. Inhabitant behavior with respect to ventilation - A summary Report of IEA Annex VIII. Technical note AIVC 23.
- Erhorn H., 1988. Influence of meteorological conditions on inhabitants' behaviour in dwellings with mechanical ventilation, *Energy and Buildings* 11, 267-275.
- Fabi V., Andersen R.V., Corngati S.P., Filippi M. And Olesen B.W. *Proceedings of Climamed11*, 2-3 June 2011, Madrid, pp. 243-258.
- Haldi F., Schweiker M., 2011. Verification of stochastic models of window opening behaviour for residential buildings. *Journal of Building Performance Simulation*. DOI: 10.1080/19401493.2011.567422.
- Herkel, S., Knapp U., and Pfafferott J., 2008. Towards a model of user behaviour regarding the manual control of windows in office buildings. *Building and Environment* 43, 588-600.
- Howard-Reed, C., Wallace L.A. and Ott W.R.. 2002. The Effect of Opening Windows on Air Change Rates in Two Homes. *Journal of air and waste management association* 52: 147-159.
- Iwashita, G., and Akasaka I. 1997. The effect of human behavior on natural ventilation rate and indoor environment in summer – a field study in southern Japan. *Energy and Buildings* 25: 195-205.
- Johnson T., Long T., 2005. Determining the frequency of open windows in residence: a pilot study in Durham, North Carolina during varying temperature conditions, *Journal of Exposure Analysis and Environmental Epidemiology* 15, 329-349.
- Keiding, L., 2003, *Environmental factors of everyday life in Denmark – with specific focus on housing environment*, edited by Lis Keiding. Statens institut for folkesundhed (SIF), København (In Danish – with English summary).
- Kvistgaard, B., Collet P.F., and Kure J.. 1985. Research on fresh-air change rate: 1 - Occupants' influence on air-change, 2.ed, *Building Technology*, The technological institute of Copenhagen, EEC Contract No. EEA-5-052-DK EFP-80 J.No. 5723.
- Kvistgaard, B., and Collet P.F.. 1990. The User's Influence on Air Change, Air Change Rate and Air Tightness in Buildings. ASTM. STP 1067, M. H. Sherman, Ed., American Society for Testing and Materials, Philadelphia, pp. 67-76.
- Price, P.N., and Sherman M.H.. 2006. Ventilation Behavior and Household Characteristics in New California Houses, Ernest Orlando Lawrence Berkeley National Laboratory, LBNL 59620.
- Offermann F., Brennan S., Hodgson A., and Jenkins P. 2008. Window usage, ventilation, and formaldehyde

concentrations in new California homes. Proceedings of The 11th International Conference on Indoor Air Quality and Climate, Indoor Air 2008, Copenhagen, Denmark, Paper ID: 767.

Van Dongen J.E.F., 2007. Occupant behaviour and attitudes with respect to ventilation of dwellings. Contributed Report 08, IEA.

Wallace L.A., Emmerich S.J., and Howard-Reed C.. 2002. Continuous measurements of air change rates in an occupied house for 1 year: The effect of temperature, wind, fans, and windows. *Journal of Exposure Analysis and Environmental Epidemiology* 12: 296-306.

Weihl, J., 1986. Monitored residential ventilation behaviour: a seasonal analysis. Proceedings from the ACEEE 1986 summer study on energy efficiency in buildings. Santa Cruz, California: 7230-45.